

Expectations for high energy diffuse galactic neutrinos for different cosmic ray distributions

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The interaction of cosmic rays with the gas contained in our Galaxy is a guaranteed source of diffuse high energy neutrinos. We provide expectations for this component by considering different assumptions for the cosmic ray distribution in the Galaxy which are intended to cover the large uncertainty in cosmic ray propagation models. We calculate the angular dependence of the diffuse galactic neutrino flux and the corresponding rate of High Energy Starting Events in IceCube by including the effect of detector angular resolution. Moreover we discuss the possibility to discriminate the galactic component from an isotropic astrophysical flux. We show that a statistically significant excess of events from the galactic plane in present IceCube data would favour models in which the cosmic ray density in the inner galactic region is much larger than its local value, thus bringing relevant information on the cosmic ray radial distribution.

I. INTRODUCTION

In four years of data taking, the IceCube detector has detected 54 High Energy Starting Events (HESE) with deposited energy between 20 TeV and 2 PeV which are compatible with an astrophysical population of high energy neutrinos [1–6]. The observed excess has been also confirmed by independent observation of upward going passing muons in IceCube [4]. The origin of these neutrinos is still unknown and potential sources include supernova remnants [7], pulsars [8], active galactic nuclei [9] and starburst galaxies [10]. Dedicated searches for point-like or extended sources have been performed by IceCube [11, 12]; however, at present, no significant clustering or correlation of event arrival directions with potential source distributions has been found, thus leaving open the possibility of a diffuse astrophysical neutrino population.

The isotropic distribution of the IceCube high energy events can be considered as an argument in favor of extragalactic origin of the signal [13–15]. Recent works, however, pointed out that IceCube data do not exclude (or are even better fitted) by allowing for a non negligible contribution of galactic origin [16–20]. It is known that the interactions of Cosmic Rays (CR) with the interstellar medium is a guaranteed source of a diffuse neutrinos in our Galaxy. The calculation of this component is, however, quite uncertain because it requires the knowledge of the CR distribution in all the regions of the Galaxy where the gas density is not negligible. The standard approach relies on local measurements and on the solution of CR transport equations by assuming constant diffusion in the whole Galaxy [21]. The recent results provided by Fermi-LAT [22] may challenge this scenario since they seems to indicate a dependence of the CR spectrum and distribution on the distance from the Galactic Center, as it is e.g. expected in CR propagation model characterised by radially dependent transport properties [23–25].

In this paper, we describe a self-contained calculation

of the diffuse galactic neutrino flux that allow us to discuss the expectations, uncertainties and detectability of this component in general terms, without entering in the complex problem of CR propagation in the Galaxy. We calculate the angular dependence of the galactic neutrino flux and the corresponding rate of High Energy Starting Events (HESE) in IceCube by considering different assumptions for the CR density in the Galaxy that are intended to cover the large uncertainty in CR propagation models. Namely, we assume that CR distribution is homogenous in the Galaxy (*Case A*), that it follows the distribution of galactic CR sources (*Case B*) and that it has a spectral index that depends on the galactocentric distance (*Case C*). We then discuss the perspectives for the extraction of a galactic neutrino signal from IceCube HESE data showing that only *Case C* gives a non negligible chance of detection.

The plan of the paper is the following. In the next section, we introduce the main ingredients of our calculation. In sect. III, we discuss our assumptions for the CR distribution in the Galaxy. In sect. IV, we calculate the neutrino flux as a function of neutrino energy and arrival direction. In sect. V, we calculate the expected rates of HESE in IceCube, taking into account the different angular resolution for shower and track events, and we discuss the perspectives for the extraction of the galactic neutrino signal. In sect. VI, we summarise our results.

II. NOTATIONS

The flux of high energy neutrinos produced at Earth by interactions of CRs with the gas contained in the galactic disk can be written as:

$$\varphi_\nu(E_\nu, \hat{n}_\nu) = \frac{1}{3} \sum_{\ell=e,\mu,\tau} \left[\int_{E_\nu}^{\infty} dE \frac{d\sigma_\ell(E, E_\nu)}{dE_\nu} \int_0^\infty dl \varphi_{\text{CR}}(E, \mathbf{r}_\odot + l \hat{n}_\nu) n_{\text{H}}(\mathbf{r}_\odot + l \hat{n}_\nu) \right] \quad (1)$$

where E_ν and \hat{n}_ν indicate the neutrino energy and arrival direction, $d\sigma_\ell/dE_\nu$ is the differential cross section for production of neutrinos ν_ℓ and antineutrinos $\bar{\nu}_\ell$ by a nucleon of energy E in nucleon-nucleon collision. The function $\varphi_{\text{CR}}(E, \mathbf{r})$ represents the differential CR flux (see next section), $n_{\text{H}}(\mathbf{r})$ is the gas density distribution and $r_\odot = 8.5$ kpc is the position of the Sun. In the above relation, we assumed that, due to neutrino mixing, the neutrino flux at Earth is equally distributed among the different flavours. This approximation is valid with few % accuracy, as it is discussed in e.g. [28] and it is completely adequate for our purposes. For the nucleon-nucleon cross section, following [29], we assume:

$$\sum_{\ell=e,\mu,\tau} \frac{d\sigma_\ell(E, E_\nu)}{dE_\nu} = \frac{\sigma(E)}{E} F(x, E), \quad (2)$$

where $x = E_\nu/E$ and the total inelastic cross section $\sigma(E)$ is given by:

$$\sigma(E) = 34.3 + 1.88 \ln(E/1\text{TeV}) + 0.25 \ln(E/1\text{TeV})^2 \text{ mb.}$$

The adimensional distribution function $F(x, E)$ is given by:

$$F(x, E) = [F_{\nu_\mu}(x, E) + F_{\nu_e}(x, E)], \quad (3)$$

where $F_{\nu_\mu}(x, E)$ and $F_{\nu_e}(x, E)$ are described (with 20% accuracy) by the analytic formulas given in [29].

The galactic distribution of the gas density, $n_{\text{H}}(\mathbf{r})$, is taken from the public GALPROP code [30] and described in [31]. This is given as a sum of atomic, H_I , and molecular H_2 hydrogen. For the latter we adopt a conversion factor with respect to the CO density as given by [27] from a fit of the diffuse γ emission. Finally, we assume that Helium contributes to the Galactic gas with a constant density ratio of 0.11 with respect to total Hydrogen.

III. THE CR FLUX

In order to predict the neutrino flux at $E_\nu \simeq 100$ TeV, we need to know the CR flux at $E \simeq 20$ $E_\nu = 2$ PeV. At the Sun position, the CR flux is constrained by observational data and we can write:

$$\varphi_{\text{CR},\odot}(E) \equiv \sum_A A^2 \frac{d\phi_A}{dE_A d\Omega_A}(AE)$$

where $d\phi_A/dE_A d\Omega_A$ is the differential flux at Earth of a given nuclear species, A represents the nuclear mass

number and we considered that the energy of the nucleus is $E_A = AE$. We use the parameterisations for $d\phi_A/dE_A d\Omega_A$ given by [16] that are obtained by fitting the CREAM [32], KASCADE [33] and KASCADE-Grande [34] data in the energy range $E_A \sim 1 - 10^6$ TeV and assuming that the dominant contributions to the nucleon flux $\varphi_{\text{CR},\odot}(E)$ are provided by H and ^4He nuclei. Note that, if large fluxes of heavy nuclei are introduced at expenses of H and ^4He components (i.e. maintaining $\sum_A d\phi_A/dE_A d\Omega_A = \text{const}$), the nucleon flux $\varphi_{\text{CR},\odot}(E)$ is reduced because the CR spectral distributions are decreasing with energy faster than E^{-2} .

The local determination $\varphi_{\text{CR},\odot}(E)$ has to be related to the CR flux in all the regions of the Galaxy where the gas density is not negligible. We consider here three different prescriptions of increasing complexity that correspond to different amounts of energy stored in CR.

Case A: We assume that the CR flux is homogenous in the Galaxy, i.e. we write:

$$\varphi_{\text{CR}}(E, \mathbf{r}) \equiv \varphi_{\text{CR},\odot}(E) \quad (4)$$

In this assumption, the neutrino flux can be expressed as:

$$\varphi_\nu(E_\nu, \hat{n}_\nu) = \mathcal{F}_\nu(E_\nu) \mathcal{A}(\hat{n}_\nu) \quad (5)$$

where the function that contains the angular dependence:

$$\mathcal{A}(\hat{n}_\nu) = \frac{1}{4\pi \mathcal{N}_{\text{H}}} \int_0^\infty dl n_{\text{H}}(\mathbf{r}_\odot + l \hat{n}_\nu) \quad (6)$$

is proportional to the column density of the gas along a given direction, the normalisation parameter \mathcal{N}_{H} is the average column density of the gas given by:

$$\mathcal{N}_{\text{H}} = \frac{1}{4\pi} \int d^3r \frac{n_{\text{H}}(\mathbf{r}_\odot + \mathbf{r})}{r^2} = 2.19 \times 10^{21} \text{ cm}^{-2} \quad (7)$$

and the function:

$$\mathcal{F}_\nu(E_\nu) = \frac{4\pi}{3} \mathcal{N}_{\text{H}} \int_{E_\nu}^\infty \frac{dE}{E} \sigma(E) F\left(\frac{E_\nu}{E}, E\right) \varphi_{\text{CR},\odot}(E) \quad (8)$$

is the neutrino flux integrated over arrival directions.

Case B: We assume that the CR flux scales proportionally to the distribution of CR sources, as it is roughly expected if CR escape is much faster from the halo than radially. Namely, we write:

$$\varphi_{\text{CR}}(E, \mathbf{r}) \equiv \varphi_{\text{CR},\odot}(E) g(\mathbf{r}) \quad (9)$$

where:

$$g(\mathbf{r}) = \frac{n_{\text{S}}(\mathbf{r})}{n_{\text{S}}(\mathbf{r}_\odot)} \quad (10)$$

and $n_{\text{S}}(\mathbf{r})$ describes the CR source density. In this assumption, the neutrino flux can still be factorised as in eq.(5) but the function $\mathcal{A}(\hat{n}_\nu)$ is replaced by the function:

$$\mathcal{B}(\hat{n}_\nu) = \frac{1}{4\pi \mathcal{N}_{\text{H}}} \int_0^\infty dl n_{\text{H}}(\mathbf{r}_\odot + l \hat{n}_\nu) g(\mathbf{r}_\odot + l \hat{n}_\nu) \quad (11)$$

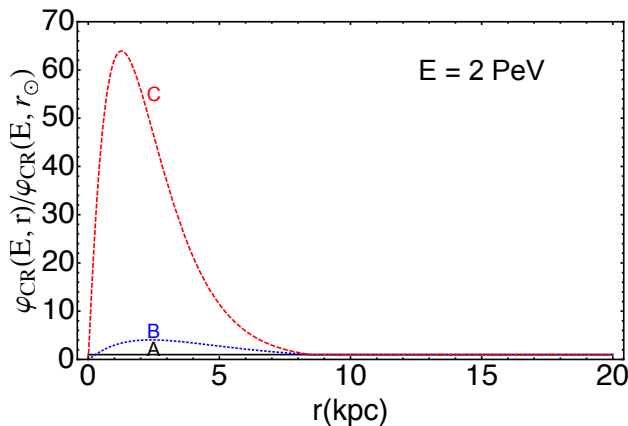


FIG. 1. The CR flux at $E = 2$ PeV as a function of the distance from the galactic center in the three considered scenarios. We assume that the CR flux is approximately constant along the galactic latitudinal axis. See text for details.

We take the SNRs distribution parameterised by Green et al. [35] as representative for the source density $n_S(\mathbf{r})$. However, since it is known, e.g. from Fermi-LAT observations of the galactic γ -ray emission [22], that in the outer region of the Galaxy the CR density drops slower than what one would expect from SNRs [35] (or pulsars [36]) distributions, we use eqs.(9) only for galactocentric distances $r \leq r_{\odot}$. Moreover, since the CR diffusion length is expected to be larger than both the thickness of the Galactic Disk and of that of the SNRs distribution, we assume that the CR flux is constant along the galactic latitudinal axis. In these assumptions, the function $g(\mathbf{r})$ is given in galactic cylindrical coordinates by:

$$g(r, z) = \left(\frac{r}{r_{\odot}}\right)^{\gamma} \exp\left(-\beta \frac{r - r_{\odot}}{r_{\odot}}\right) \quad (12)$$

where $\gamma = 1.09$, $\beta = 3.87$ and we neglected the dependence on z . The function $g(\mathbf{r})$ is shown by the blue line in Fig.1. We see that the CR density is larger by a factor ~ 4 at distances $r = 2 - 3$ kpc from the galactic center with respect to its local value. To provide a quantitative comparison, we note that the energy stored in CR contained at $r \leq r_{\odot}$ is a factor 2.3 larger than what obtained in the assumption of CR homogeneity.

Case C: We consider the possibility that the CR spectral distribution depends on the position, as it has been recently observed by Fermi-LAT at low energies [22, 26, 27]. To this purpose, we write:

$$\varphi_{CR}(E, \mathbf{r}) \equiv \varphi_{CR, \odot}(E) g(\mathbf{r}) h(E, \mathbf{r}) \quad (13)$$

where the function:

$$h(E, \mathbf{r}) = \left(\frac{E}{\bar{E}}\right)^{\Delta(\mathbf{r})} \quad (14)$$

introduces a position-dependent variation $\Delta(\mathbf{r})$ of the CR spectral index. The pivot energy in eq.(14) is taken as $\bar{E} = 20$ GeV, since it is observed [22, 23] that the integrated CR density above 20 GeV roughly follows the function $g(\mathbf{r})$ defined in *Case B*.

Having no direct informations on the radial distribution of high energy CR, we are forced to rely on extrapolations from low energy data and even a relatively small $\Delta(\mathbf{r})$ may introduce a large error. At the energy $E_{CR} = 2$ PeV which is most relevant for neutrino telescopes, the major effect of the function $h(E, \mathbf{r})$ is to rescale the CR flux by a factor

$$\bar{h}(\mathbf{r}) = \left(\frac{E_{CR}}{\bar{E}}\right)^{\Delta(\mathbf{r})} \quad (15)$$

that depends on the position but that can be approximately considered energy-independent. In this assumption, the neutrino flux is still given by eq.(5) but the function $\mathcal{A}(\hat{n}_{\nu})$ is replaced by:

$$\mathcal{C}(\hat{n}_{\nu}) = \frac{1}{4\pi\mathcal{N}_H} \int_0^{\infty} dl n_H(\mathbf{r}_{\odot} + l \hat{n}_{\nu}) g(\mathbf{r}_{\odot} + l \hat{n}_{\nu}) \bar{h}(\mathbf{r}_{\odot} + l \hat{n}_{\nu}). \quad (16)$$

For our calculations, we take the function:

$$\Delta(r, z) = 0.3 \left(1 - \frac{r}{r_{\odot}}\right) \quad (17)$$

for $r \leq r_{\odot}$, in galactic cylindrical coordinates, that is intended to reproduce the trend of the spectral index with r observed by [22] at 20 GeV and that is also used by [24] in their phenomenological CR propagation model characterised by radially dependent transport properties. This corresponds to increasing the CR flux at $E_{CR} = 2$ PeV by a factor $(E_{CR}/\bar{E})^{0.3} \simeq 30$ close to the galactic center with respect to *Case B*.

The product $g(\mathbf{r})\bar{h}(\mathbf{r})$ is shown by the red dashed line in Fig. 1 from which we see that the CR density at 2 PeV is larger by a factor ~ 60 at distances $r = 2 - 3$ kpc from the galactic center with respect to its value at the Sun position. The energy stored in CR above 2 PeV at distances $r \leq r_{\odot}$ is a factor 14 larger than what obtained in the assumption of CR homogeneity (i.e. *case A*).

IV. THE NEUTRINO FLUX

In the three cases described above, the flux of high energy neutrinos and antineutrinos of each flavour at Earth can be written as:

$$\varphi_{\nu}(E_{\nu}, \hat{n}_{\nu}) = \mathcal{F}(E_{\nu}) \mathcal{I}(\hat{n}_{\nu}) \quad (18)$$

where $\mathcal{I} = \mathcal{A}, \mathcal{B}, \mathcal{C}$ depending on the considered scenario. Being $\bar{\mathcal{A}} \equiv \int d\Omega \mathcal{A}(\hat{n}) = 1$, the function $\mathcal{F}(E_{\nu})$ represent the angle-integrated neutrino flux in the *Case A* (i.e. uniform CR density). For neutrino energies

$E_\nu = 10 \text{ TeV} - 1 \text{ PeV}$, this is well approximated by:

$$\mathcal{F}(E_\nu) = f \left[\frac{E_\nu}{100 \text{ TeV}} \right]^{-\alpha(E_\nu)} \quad (19)$$

where $f = 4.76 \times 10^{-7} \text{ GeV}^{-1} \text{ m}^{-2} \text{ y}^{-1}$ and the spectral index is given by:

$$\alpha(E_\nu) = 2.65 + 0.13 \log_{10} (E_\nu/100 \text{ TeV}). \quad (20)$$

Note that the functions $\mathcal{B}(\hat{n}_\nu)$ and $\mathcal{C}(\hat{n}_\nu)$ are not normalized. The integrated neutrino fluxes in these scenarios are thus given by:

$$\phi_\nu(E_\nu) = \bar{\mathcal{I}} \mathcal{F}_\nu(E_\nu) \quad (21)$$

where the factors $\bar{\mathcal{I}} \equiv \int d\Omega \mathcal{I}(\hat{n})$ are equal to $\bar{\mathcal{B}} = 1.23$ and $\bar{\mathcal{C}} = 2.34$, respectively.

The angle-integrated fluxes can be compared with the isotropic flux:

$$\mathcal{F}_{\text{iso}}(E_\nu) = f_{\text{iso}} \left[\frac{E_\nu}{100 \text{ TeV}} \right]^{-2.58} \quad (22)$$

where $f_{\text{iso}} = 8.72 \times 10^{-6} \text{ GeV}^{-1} \text{ m}^{-2} \text{ y}^{-1}$, that corresponds to the HESE event rate observed by IceCube in four years data taking [37]. At the neutrino energy $E_\nu = 100 \text{ TeV}$ that provides the most relevant contribution to the HESE data sample, the diffuse galactic neutrino component is equal to 5%, 7% and 13% in *Case A*, *B* and *C* respectively, of the isotropic flux required to explain the 54 events observed by IceCube. This component is thus not negligible but always subdominant and well consistent with the upper limit derived from [16] by fitting the event arrival directions.

The angular dependence of the flux in the three considered scenarios is shown in Fig. 2 as a function of the galactic longitude l (left panel) and latitude b (right panel). We note that:

i) In the considered scenarios, it always exists a region, that contains the galactic center, where the neutrino flux produced by CR interacting with the gas contained in the galactic disk, is comparable or larger than the isotropic contribution. Thus, the diffuse galactic neutrino component is, in principle, sufficiently intense to be detected. We recall that this component is guaranteed by the existence of CR at PeV energies, as it is observed e.g. by CREAM, KASCADE and KASCADE-Grande experiments. Our calculations are based on the local determination of the CR flux $\varphi_{\text{CR},\odot}(E)$ described in sect.III. We warn the reader that other interpretations of the experimental data are possible [38] which may decrease the neutrinos flux by a factor ~ 2 [16] without altering, however, our conclusions;

ii) The region where the diffuse galactic neutrino component dominates is quite narrow. Even in the most optimistic *Case C*, the region where $\varphi_\nu(E_\nu, \hat{n}_\nu) \geq \mathcal{F}_{\text{iso}}(E_\nu)/4\pi$ corresponds to $|l| \leq 70^\circ$ and $|b| \leq 3^\circ$. Thus, the optimal detector should have a good pointing capability in order to avoid diluting the signal below the

TABLE I. The track and shower HESE rates expected in IceCube for the three different models considered in the text and for the isotropic flux observed by IceCube. We also show the separate contributions from Northern and Southern hemisphere.

	$N/T - \text{counts} \cdot \text{y}^{-1}$			
	<i>Showers</i>	<i>Tracks</i>	<i>North</i>	<i>South</i>
<i>Case A</i>	0.40	0.07	0.18	0.29
<i>Case B</i>	0.50	0.09	0.20	0.39
<i>Case C</i>	1.01	0.19	0.27	0.92
<i>Isotropic</i>	8.33	1.61	4.13	5.80

isotropic background. Unfortunately, the IceCube HESE data set is dominated by showers events that do not allow to reconstruct the neutrino arrival direction with sufficient accuracy (see next section, for a detailed discussion).

iii) The angular distributions are quite different in the three considered cases. The maximal emission is always achieved for $l \simeq \pm 25^\circ$ and $b = 0^\circ$ but the neutrino fluxes may differ by large factors for $|l| \leq 90^\circ$. To be quantitative, the flux from the galactic center is larger by a factor ~ 2 and ~ 11 in *Case B* and *C* respectively, with respect to the value obtained in the assumption of uniform CR density (i.e. *Case A*). In perspective, this could provide an handle to discriminate among different scenarios, in an ideal detector with sufficient statistics and good pointing capability.

V. EVENT RATE IN ICECUBE

The number of HESE event expected in IceCube can be calculated by using the effective areas $A_\ell(E_\nu, \hat{n}_\nu)$ provided by [39] according to:

$$\begin{aligned} N_S &= T \int dE_\nu \int d\Omega_\nu \varphi_\nu(E_\nu, \hat{n}_\nu) [A_e(E_\nu, \hat{n}_\nu) + \\ &\quad A_\mu(E_\nu, \hat{n}_\nu)(1 - \eta) + A_\tau(E_\nu, \hat{n}_\nu)] \\ N_T &= \eta T \int dE_\nu \int d\Omega_\nu \varphi_\nu(E_\nu, \hat{n}_\nu) A_\mu(E_\nu, \hat{n}_\nu) \end{aligned} \quad (23)$$

where T is the observation time and we estimated the separate contributions of shower (N_S) and track (N_T) events. In the above relation, we assume that neutrinos and antineutrinos are equally distributed among the different flavours, as it is expected due to flavour oscillations; moreover, we indicate with $\eta \simeq 0.8$ the probability that a muon neutrino interacting in IceCube produces a track event, as it was estimated in [28]. This parameter is somewhat uncertain and may be reduced by systematic tracks misidentification error [40]. We remark, however, that the specific value of η does not alter our main conclusions.

The event rates corresponding to the three scenarios considered in this paper are given in Tab.I where we

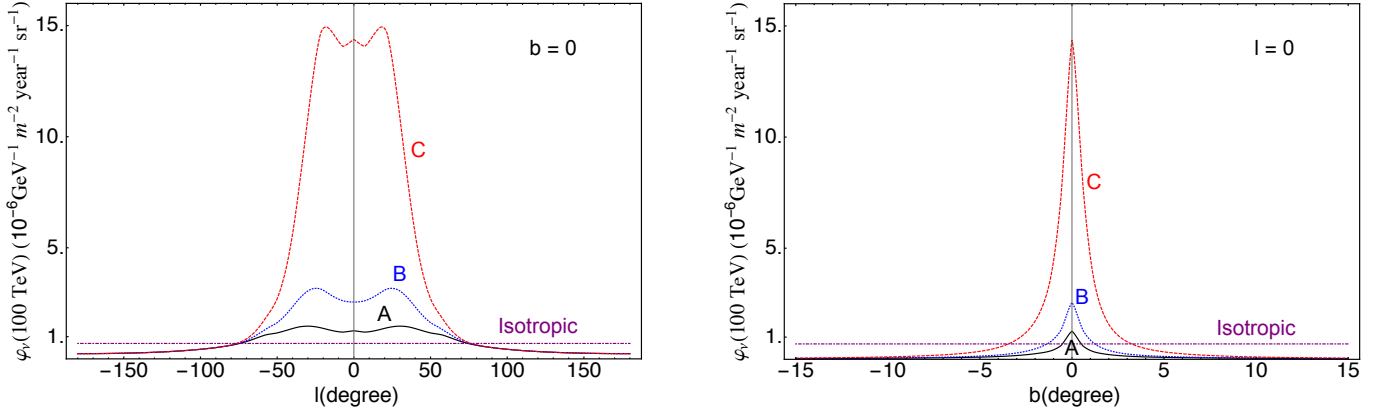


FIG. 2. The neutrino flux at $E_\nu = 100 \text{ TeV}$ as a function of the Galactic longitude (left panel) and latitude (right panel) for the three different models considered for CR distribution. The solid black line corresponds to *Case A*, the blue dotted line corresponds to *Case B* and the red dashed line corresponds to *Case C*. The isotropic flux that reproduces IceCube HESE data is also reported for comparison with a purple dot-dashed line.

also give the separate contributions from the Northern and Southern hemisphere, calculated by taking into account the angular resolution of the IceCube detector as it is described below. In the assumption of uniform CR density (*Case A*), one obtains a total event rate $(N_S + N_T)/T = 0.47 \text{ y}^{-1}$. For *Case B* and *Case C*, the predicted event rates are $(N_S + N_T)/T = 0.60 \text{ y}^{-1}$ and $(N_S + N_T)/T = 1.2 \text{ y}^{-1}$, respectively. For comparison, the isotropic flux corresponds to an integrated rate $(N_S + N_T)/T = 9.9 \text{ y}^{-1}$. We also see that the North-South asymmetry depends on the considered scenario, being maximal and equal to $\sim 55\%$ for *Case C*, as a result of a more pronounced emission from the inner Galactic region. In view of the smallness of the diffuse galactic neutrino contribution, it appears however unfeasible that this component may introduce of a large North-South asymmetry in the complete IceCube HESE data sample (see [17] for a discussion).

The angular distribution of events can be estimated by:

$$\begin{aligned} \frac{dN_S(\hat{n})}{d\Omega} &= T \int dE_\nu \int d\Omega_\nu G_S(\hat{n}, \hat{n}_\nu) \varphi_\nu(E_\nu, \hat{n}_\nu) \\ &\quad \times [A_e(E_\nu, \hat{n}_\nu) + A_\mu(E_\nu, \hat{n}_\nu)(1 - \eta) + A_\tau(E_\nu, \hat{n}_\nu)] \\ \frac{dN_T(\hat{n})}{d\Omega} &= \eta T \int dE_\nu \int d\Omega_\nu G_T(\hat{n}, \hat{n}_\nu) \\ &\quad \varphi_\nu(E_\nu, \hat{n}_\nu) A_\mu(E_\nu, \hat{n}_\nu) \end{aligned} \quad (24)$$

where the function $G_S(\hat{n}, \hat{n}_\nu)$ ($G_T(\hat{n}, \hat{n}_\nu)$) describes the angular resolution, i.e. the probability that a shower (track) event with a *reconstructed* direction \hat{n} is produced by a neutrino arriving from the direction \hat{n}_ν . In principle, the angular resolution depends on the neutrino energy, flavour, direction, etc. Here, to avoid unnecessary complications, we take constant angular resolution for

showers and track events, modeled as [41]:

$$G_I(\hat{n}, \hat{n}_\nu) = \frac{m}{2\pi\delta n_I^2} \exp\left(-\frac{1-c}{\delta n_I^2}\right) \quad (25)$$

where $I = S, T$, the parameter m is a normalization factor, $c \equiv \cos\theta = \hat{n} \cdot \hat{n}_\nu$ and the widths δn_S and δn_T are calculated by requiring that $\theta \leq 15^\circ$ at 68.3% C.L. for showers and $\theta \leq 1^\circ$ at 68.3% C.L. for tracks [37].

The results of our calculations are shown in Fig.3. We see that, due to the poor pointing accuracy, the showers produced by diffuse galactic neutrinos are diluted below the isotropic component everywhere in the sky, except for the most favorable *Case C*. On the contrary, the track rate remains dominant in a narrow region of the sky containing the galactic center. The expected track rate is, however, very small (see tab. I) making it difficult to obtain a non negligible detection probability.

We can estimate the chance of extracting the diffuse galactic component from the HESE IceCube data sample, by evaluating the fractional error δN_I in the determination of an excess N_I of track or shower events in a specific region of the sky with respect to the expectations $N_{I,\text{iso}}$ in the same region from an isotropic flux. We obtain:

$$\delta N_I \simeq \sqrt{\frac{1+\rho}{N_I}} \quad (26)$$

where $I = S, T$, the parameter $\rho = N_{I,\text{iso}}/N_I$ represents the background-to-signal ratio in the adopted observation window and we neglected systematical error sources. We consider for definiteness *Case C* since this is the only scenario in which we obtain a non negligible chance of detection due to the fact that it predicts a larger and more pronounced emission from the inner galactic region. In this specific case, the optimal observation window for showers is given by $|l| \leq 60^\circ$ and $|b| \leq 15^\circ$, for which we

obtain:

$$\delta N_S = \frac{1.9}{\sqrt{T/1\text{y}}}. \quad (27)$$

For tracks, the optimal region is given by $|l| \leq 80^\circ$ and $|b| \leq 3^\circ$ for which we have:

$$\delta N_T = \frac{3.3}{\sqrt{T/1\text{y}}}. \quad (28)$$

The above results show that an observation time $T \geq 4\text{y}$ for showers and $T \geq 11\text{y}$ for tracks is necessary to obtain 1σ hints for a galactic neutrino component, i.e. $\delta N_S \leq 1$ and/or $\delta N_T \leq 1$. For comparison, observation times larger than 35 years and 20 years are required to obtain a comparable significance for *Case A* and *Case B*, respectively. This allow us to conclude that the detection of a statistically significant excess of events from the galactic plane in present (or next future) IceCube HESE data, as e.g. suggested by [18, 19], would require relatively large galactic fluxes, favoring scenarios similar to our *Case C* in which the CR density in the inner galactic region is greatly enhanced with respect to its local value (see fig.1).

VI. CONCLUSIONS

In this paper, we have calculated the angular dependence of the diffuse galactic neutrino flux and the corresponding IceCube HESE rate by considering different assumptions for the CR density in the Galaxy. Namely, we have assumed that CR distribution is homogenous in the Galaxy (*Case A*), that it follows the distribution of galactic CR sources (*Case B*) and that it has a spectral index that depends on the galactocentric distance (*Case C*). Our conclusions are summarised in the following:

i) In the considered scenarios, the angle-integrated galactic neutrino flux at 100 TeV is always subdominant with

respect to the isotropic contribution required to fit IceCube HESE data. However, it always exists a region of the sky, that contains the galactic center, where the galactic component is comparable or larger than the isotropic contribution.

ii) While the angle-integrated flux vary at most by a factor ~ 2 , the angular distribution of the diffuse galactic component is strongly dependent on the assumed CR distribution. In perspective, this provides an handle to discriminate among different scenarios, in an ideal detector with sufficient statistics and good pointing capability;

iii) The poor angular resolution for shower events and the smallness of the expected rate limit the possibility to extract the diffuse galactic neutrino contribution from the IceCube HESE data. In our analysis, only *Case C* has a non negligible chance of detection, due to the fact that it predicts a larger and more pronounced emission from regions close to the galactic center. In the optimal region of the sky given by $|l| \leq 60^\circ$ and $|b| \leq 15^\circ$, we expect ~ 2.5 HESE events in four years of data-taking that could be observed with $\sim 1\sigma$ significance above the isotropic contribution. Note that the future KM3NeT [43] should be in better position, having the possibility to observe the inner galactic region with a relatively large exposure by using up-going passing muons;

iv) If a statistically significant excess of events from the galactic plane will be observed in present or next future IceCube HESE data, as e.g. suggested by [17, 18, 24], this would favour models similar to our *Case C*, in which the CR density in the inner galactic region is much larger than its local value, thus bringing relevant information on the CR radial distribution.

As a final remark, since the major obstacle for the detection of diffuse galactic neutrinos in IceCube is the smallness of the expected event rates (at level of $\sim 1\text{y}^{-1}$ at most), it would be interesting to explore the possibility of increasing the statistics (at the level of $\sim \text{few y}^{-1}$ at least) by lowering the detection threshold, as it was done e.g. in [42] and [12].

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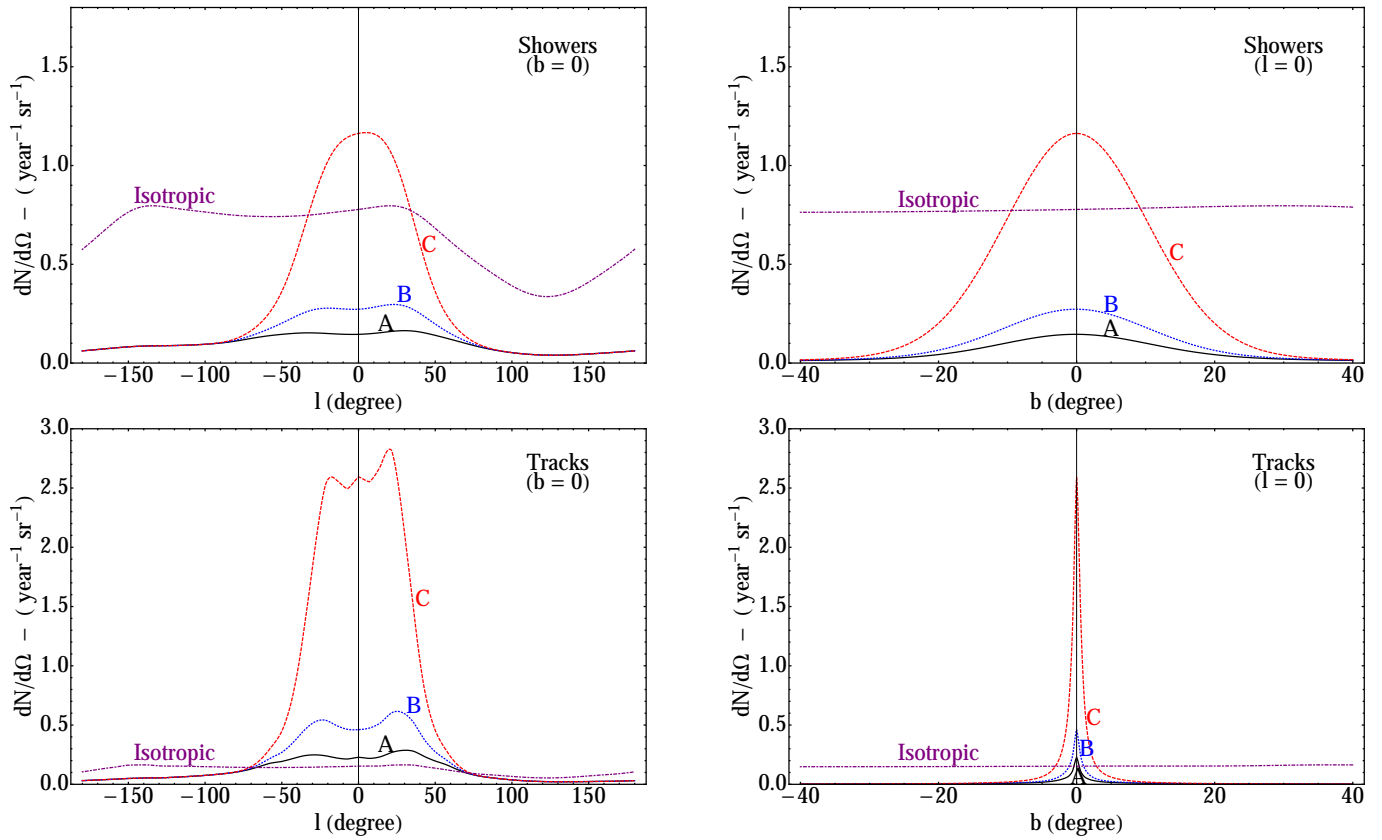


FIG. 3. The HESE rate expected in IceCube as a function of the galactic longitude (left panels) and galactic latitude (right panels) for the three different models considered in this work and for the isotropic flux that reproduces IceCube data. The legend of the different lines is that discussed in our previous plots. Upper panels refer to shower events whereas lower panels refer to track events.

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